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Methodologies to Reduce Cooling Load using Heat Balance Analysis: A Case Study in an Office Building in a Tropical Country

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Abstract

The world is experiencing energy crisis since the 1970s due to the limitation in fossil fuel resources and increasing energy demand as a result of industrialisation and development which have taken place all over the world [1]. It is reported by International Energy Agency (IEA) that 32% of the total worldwide energy consumption was contributed by building sector [2]. Researchers found that Heating Ventilation and Air Conditioning (HVAC) system consumed the highest amount of energy in commercial building [3,4,5,6,7] meanwhile in tropical countries more than 50% of the building's energy were used for air conditioning [8]. This research found that standard building can be transformed into Low Energy Office building by applying heat gain reduction methodologies draws from heat balance analysis. An office building in Malaysia was audited and modelled in Design Builder software for heat balance analysis. It is found that 75% of the building's heat gain was radiated from lighting system and solar heat gain through window. It is estimated that 45.85% of building's energy can be saved by changing the zones temperature set point, modification in lighting system and building's glazing for daylight optimization and minimizing solar heat gain. Besides energy saving, the building's indoor environmental quality based on MS1525:2007 and occupants' comfort was ensured too. A basic cost analysis estimated in the software shows that the highest increment in initial cost for the methodologies suggested was only 1.32%, hence this study shows that a sustainable building does not necessarily induced high cost for the technologies implementation if the right technologies were chosen to suit the building's condition.

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Keywords: Applied Energy; Energy Efficiency; Sustainable Building, Cooling System.

Introduction

A typical Malaysia Office Building consumes about 250 kWh/m²/year which is 400% higher than suggested building energy index (BEI) for green energy office (GEO) building [7,9,10]. The study by Chan and S.Aun found that on average, Malaysia office building used 64% of the total building's energy for air conditioning while other tropical countries such as, Indonesia, Thailand and Singapore, spent 51% to 59% of the building's energy on air conditioning [11]. Studies were conducted to reduce cooling energy from buildings by the implementation of passive cooling, high efficient cooling technologies and operative control. Graca et al showed that introducing natural ventilation system in a mall can reduce 30% of overall HVAC system's energy consumption for Mediterranean weather [12]. Park et al found that HVAC system draws 75% of total building's gas usage and lighting draws 38.9% of the building's total electrical consumption. The energy reduction plan proposed includes controlling the scope of the external lighting, adopting an economizer, utilizing low-e glass and condensing boiler [13]. A study by Wen-Pei Sung et al found that an air conditioning system with Variable Volume system could save up to 46% energy consumption compared to a

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Constant Volume system [14]. Y.H Zurigat studied application of passive cooling technologies in a school in Oman, Saudi Arabia found that energy can be reduced up to 43% by using combination of well-established technologies [15]. Air conditioning is a process to condition air quality to a specific temperature and humidity for the occupants' comfort. The total cooling load for a space cooling depends on the latent and sensible cooling load where sensible cooling load arises from solar heat gain, lighting system, people, and equipment. Meanwhile latent load arises from people, outdoor air leakage and processes such as steaming. The aim of this research is to; (a) study the energy trend in a building, (b) discover the main heat resources in a building in a tropical country and (c) to design methodologies to reduce building's energy consumption focusing on cooling load reduction.

2. Building Case Study

A medium size government office building was used as the building case study. It is located in Putrajaya, Malaysia (Lat 3.12°, longitude 101.55°) experiencing hot and humid weather trough out the year. The building's gross floor area is 47,708 m² with 351 total occupants. It consists of 2 underground floors, a ground floor and 7 office floors. Its air conditioning was served by a unitary constant air volume system, AHU systems in every floor, fan coil air conditioning units for lifts and the chilled water was supplied by Gas District Cooling Plant.

3. Building's Energy Audit

The building's floor plan, equipment data, equipment operation schedule, indoor environmental quality measurements, energy bills and energy consumption data were gathered and analysed. The data was taken from building's annual energy audit reports performed by a legal energy consultant (consist of building energy bills, end-use energy performance for 2012, indoor air quality measurement, list of equipment and their specification), personal interview with building's energy manager and engineers, and site visit. The building is equipped with energy monitoring system (Circutor Power Studio Scada by Monitor Power Energy) to monitor the cooling system. The building's chilled water was supplied by Gas District Plant and measured in refrigeration ton per hour (RTH) hence the building's total energy consumption in kWh was calculated by using the equation (1) and (2). The BEI was calculated using the equation (3).

$$\textit{Annual energy consumption (AEC)} = \sum El + \sum CW(kWh) \tag{1}$$

Where; $$CW(kWh) = \frac{CW\ (RTH)\ x\ 3.5}{Chiller's\ C.O.P} \tag{2}$$

$$BEI = \frac{\sum AEC}{\sum FA} \tag{3}$$

Where ; CW(RTH) is the chilled water consumption in refrigeration tone per hour; CW(kWh) is the chilled water consumption in kilowatt per hour; El is the annual electrical consumption and FA is the Building's floor area (m²)

The average BEI within 4 years, 2009 to 2012 was 238.53 kWh/m²/year. It is slightly lower than the typical BEI of Malaysia's office building, 250 kWh/m²/year [9,10] and quite similar with BEI of Malaysia's public hospital, 234 kWh/m²/year studied by Saidur et al [11]. However, the BEI value is comparatively lower compared to the average office's BEI in Europe (306 kWh/m²/year) [16]. The building need to reduce 46.9% of its total energy consumption to become a low energy office building (LEO). A reduction in cooling system will give a big impact in building's energy consumption since in year 2012 the sector consumed 58.9% of the building's total energy consumption and energy intensity from cooling system was 127.89 kWh/m²/year which is higher than the BEI benchmark for LEO building (114 kWh/m²/year) [17]. The building's end-use energy intensity is shown in Figure 1 (a). In year 2012, total energy consumption for cooling system was 4.32 GWh. Building's indoor environmental quality analysis was extracted from building's energy audit report, measured by Tento 540 (for lumen measurement), Psensor RH (for CO_2 measurement) and HT305 (for relative humidity and temperature measurement). The result shows that 5 out of 8 office spaces have lower than the minimum space temperature suggested by MS1525:2007 ($23^{O}C$- $26^{O}C$). Average luminance in 5 out of 8 office spaces was lower than minimum requirement (300 lux) and corridors area received a very high luminance from daylight which caused glares to the occupants. The air relative humidity level at two zones exceeded the maximum requirement (55%-70%) by less than 1.6%. Meanwhile the carbon dioxide level in the whole building was below the maximum limit stated by Malaysia's Department of Occupational of Safety and Health (less than 1000).

4. Building's modelling and validation

A model of the building case study was designed using Design Builder software version 4.2.0.034. Design Builder software is the most complete Graphical User Interface to the Energy Plus simulation engine (from US DOE). It provides easy to use software and a high quality data on energy consumption, carbon emissions, occupant comfort, and daylight availability [18]. The building's model is then validated based on the tolerance range calculated from actual monthly energy data and simulated monthly energy data. The simulation does not consider public holidays. As suggested by ASHRAE if the weather data used was recorded by the hour the building is considered accurate if the Coefficient of Variation of the Root Mean Square Error (CV(RMSE)) is below 25% [13]. The software presented total energy for cooling system as 'district cooling'. Hence, the actual energy consumption by cooling system was calculated based on the equation (4). The equation (5) is to calculate CV(RMSE) and equation (6) is to calculate percentage error between the simulation results and actual results. Simulations were carried out until the tolerance range met.

$$ECS \quad = \text{Cooling system's auxiliary energy} + CW\ (kWh) \tag{4}$$

$$CV(RMSE) = \frac{\sqrt{\left(\sum_{i=1}^{n} \frac{(MECsim,i - MECact,i)^2}{n} - 1\right.}}{Mean\ of\ MECact} \times 100\% \tag{5}$$

$$Error\ (\%) = \frac{|AECsim - AEC\ act|}{AEC\ act} \times 100\% \tag{6}$$

Where; MEC is the monthly energy consumption; n is the number of months; AEC is the annual energy consumption; 'act' is the actual and 'sim' is the simulated result.

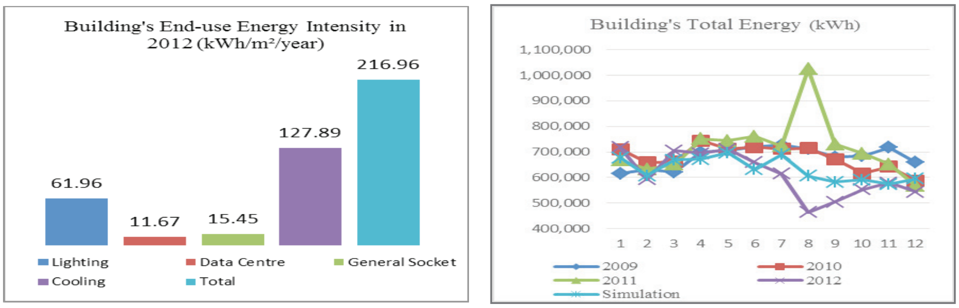

Figure 1. (a) Building's end-use energy intensity in 2012; (b) Comparison of monthly energy consumption between the actual and simulated results.

Monthly energy usage were simulated and compared to the actual billings as shown in Figure 1 (b). The percentage error calculated was 4.37% and the CV (RMSE) value is 9.57% which is below 25% tolerance value suggested by ASHRAE. The simulated energy trend matches the energy trend in 2009 and 2010 but the energy trend in August in 2011 and 2012 were both odd in trend.

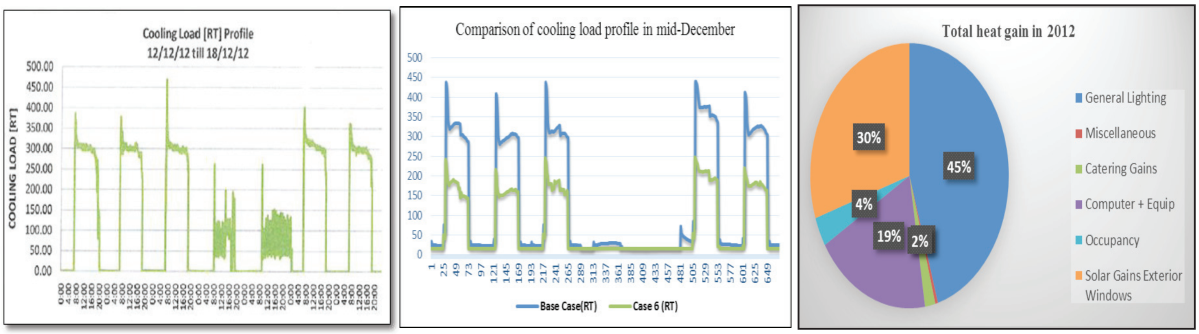

Figure 2. (a) Actual cooling load profile; (b) Simulated cooling load for base case and Case 6; (c) Heat gain distribution.

6. Methodologies to reduce building's cooling load

Cooling load methodologies were chosen to reduce heat gain from the major heat sources; lighting system and solar heat gain through window. Three approaches were chosen to reduce the cooling load. The temperature set point adjustment, modification in lighting system and glazing type. Every case are listed in Table 1 and discussed in section 3.5.1, 3.5.2 and 3.5.3 respectively. The simulation results for each case study are listed in Table 2.

Table 1. Settings for building's energy simulation

Zones	Cooling temperature set point (^{O}C)				Lighting			Glazing		
	Base case/Actual	Case 1,4,5,6,7,8	Case 2	Case 3	Base case/Actual	Case 4,6,7,8	Case 5	Case 6	Case 7	Case 8
Communal hall	23	24	24	25		Mixed types		n/a	n/a	n/a
Data centre and IT room	21	23	23	23	Fluorescent, surface mount	LED, duct air. (corridors, offices, café, lobby, toilets)	LED, recessed. (corridors, offices, café, lobby, toilets)	n/a	n/a	n/a
Corridors	26.7	26	24	25				Double glazing: generic ECREF-2 colored on generic low-e Argon 6mm/13mm	Double glazing: AGC glass copper on gray on clear glass Air 5.6mm/ 13mm	Double glazing: Solarmetrix reflective gray15 on clear glass Air 6.3mm/ 6mm.
Offices	22.6	24	24	25	Mixed types					
Cafeteria	26.5	26	24	25						
Lobby	23	26	24	25						
Toilets	n/a	n/a	n/a	n/a				n/a	n/a	n/a

6.1 Adjustment in temperature set point

The cooling temperature set points were adjusted within the suggested guideline by MS1525:2007. The result shows that Case 3 give the biggest energy reduction followed by Case 1 and Case 2. The percentage difference in energy reduction between Case 1 and Case 3 was only 0.18%. Based on the information given by building's energy manager, 24 ^{O}C is the maximum temperature set point for office areas. This is based on the feedback given by employees when the building management increased cooling temperature set point to 24 ^{O}C and 25 ^{O}C, negative feedback related to comfort were given by the employees when the cooling set point were raised to 25 ^{O}C meanwhile no complaint received when it was raised to 24 ^{O}C . Case 1 was selected after considering the energy impact and occupants' comfort.

6.2 Lighting system's modification

Even though majority of the office zones received lower than the standard light luminance' level suggested by MS1525:2007 for office space, the heat emitted by the lighting system is high. This shows that the lighting system's efficiency in the building is low and in need of improvement. Previous studies showed that lighting is one of the most cost effective ways to reduce carbon emission and application of existing technology could reduce electricity use for lighting by 50% [19]. Besides emitting visible light, a lamp also emits radiant and convective heat responsible in building heat gain. Radiant heat instantaneously promotes a heat gain into the building. The proportion of visible light and heat emission depends on type of lamp and the way a lamp was mounted. The building mainly used 36W fluorescent lamps and 70W ceramic discharge metal-halide lamp. Typical fluorescent lamps emit 21% of its input power to visible light, 37% radiant heat and 42% convective heat. Meanwhile LED emits 15-25% visible light and 75-85% convective heat [19]. The building's lamps were fixed at surface mount which emit highest radiant heat compared to other types. The radiant fractions from different lamp fixture types according to Design Builder are 72% for 'surface mount', 42% for 'suspend', 37% for 'recessed' and 'luminous louvered' and 18% for 'return air duct type' [16]. The lighting system was modified in reference to the standard luminance suggested by MS1525:2007 and aimed to increase energy efficiency and reduce heat gain from lighting system. The building's zones with long operation time were selected for the implementation of lighting system's modification. Detail lighting settings are listed in Table 1. The lighting system was equipped with automatic control system allowing automatic illumination adjustment from artificial light to maintain targeted zone's illumination level, hence optimizing the benefit of daylight received. Simulation results for Case 4 and Case 5 both showed 40.49% BEI reduction, 27.10% energy reduction in cooling system and 84.56% energy reduction in lighting system. The simulation results also shows LED lamp fitting (duct-air and recessed) does not give any different on thermal heat gain. The convective heat gain from LED light did not give a direct heat gain to the indoor environment when lighting was in operation probably due to the ceiling's low thermal conductivity. Heat gain from lighting reduced by 87.1% from 2.14 GWh annually to 0.28 GWh in a year after the implementation of Case 4 and Case 5.

6.3 Reduction of solar heat gain through window

A window is an important element to ensure an occupants' thermal comfort and in providing daylight illumination into the building. Malaysia received 16.8 MJ/m² average solar radiation a day [20] where the radiation ranges from 3% ultraviolet light (UV), 44% visible light (VL) and 53% infrared (IR). An incident solar radiation on a building's glazing partially reflected and partially transmitted into the building depending on the glazing's thermal components [21,22]. An infrared light transmitted as heat into a building meanwhile visible light increases daylight luminance. For a cooling demand country, glazing with high visible light transmittance and low infrared absorption is preferable to maximize daylight luminance and reduce heat gain. The instantaneous room heat gain is governed by the equation (7) [21].

Table 2. Results of each case study and their comparison with base case.

Case study	BEI		Energy consumption by cooling system (Ec)		Energy consumption by interior lighting (E_L)		Basic material cost for the building construction	
	(kWh/m²/year)	BEI Reduction (%)	(kWh)	Ec Reduction (%)	(kWh)	E_L Reduction (%)	(GBP)	Cost increment compared to actual building's cost (%)
Base case	207.17	n/a	3978924.3	n/a	2137000.1	n/a	32,109,184	n/a
Case 1	202.73	2.14	3826306.7	3.84	2137000.1	0	32,109,184	0
Case 2	205.28	0.91	3913979.2	1.63	2137000.1	0	32,109,184	0
Case 3	202.37	2.32	3813888.5	4.15	2137000.1	0	32,109,184	0
Case 4	123.29	40.49	2900482.2	27.1	329937.34	84.56	32,397,507	0.9
Case 5	123.29	40.49	2900482.2	27.1	329937.34	84.56	32,397,507	0.9
Case 6	112.18	45.85	2357592.7	40.75	490886.12	77.03	32,531,902	1.32
Case 7	117.12	43.47	2513437.9	36.83	504800.3	76.38	32,383,610	0.85
Case 8	119.52	42.31	2563587.6	35.57	537315.4	74.86	32,137,258	0.09

A list of available glazing in Design Builder software was studied and three types of glazing with the required preference were chosen for energy and cooling load analysis.

$$Q_i = U * (T_a - T_r) + (SHGC * G) \quad (7)$$

Where; Qi is the instantaneous solar heat gain, U is the U-factor, Ta is the ambient temperature, Tr is the room temperature, SHGC is the solar heat gain coefficient and G is the solar irradiance.

Three case studies (Case 6, 7, 8) were simulated. The detail information about glazing types in each case can be referred in Table 1. The changed in glazing types resulted in further energy reduction from cooling system and slightly increased in lighting electricity consumption due to the reduction in daylight. However, the luminance level received was better for the occupants' comfort since in actual practice high daylight exposure caused glares.

7. Conclusion

Reducing building's cooling load and increasing cooling system efficiency will give a big impact on building's energy performance. The cooling system drawn 58.9% of building's total energy consumption and its energy intensity alone (126 kWh/m²/year) has exceeded the standard energy intensity for low energy office building by 9.57%. 'Re-setting temperature set point', modification in lighting system and replacement of current glazing could reduce building's energy index to 112.18 kWh/m²/year (45.85% BEI reduction) enables it to be a low energy office building. Building's heat balance analysis is a suitable approach for an existing building planning for retrofit to improve its energy performance. This approach enable building's owner to plan for the right retrofit and estimate energy reduction based on the building's energy simulation. Based on the Design Builder's basic cost simulation, it is found that the initial cost for Case 8 is 0.09% higher than the initial cost for Base Case even though the BEI for Case 8 is 42.31% lower. Hence, designing a sustainable building does not necessarily induced high cost for the technologies implementation but it is more about choosing the right technologies to suit the building's condition.

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